Hydrogen Storage Solutions in Support of DoD Warfighter Portable Power Applications

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BACKGROUND

From Personal Digital Assistants (PDAs) to cell phones our high-tech world is demanding smaller, lighter weight and higher capacity portable power devices. Nowhere has this personal power demand been more evident than in today's US warfighter. The modern warfighter is estimated to carry from 65 to 95 pounds of supplies in the field with more than 30 pounds of this dedicated to portable power devices.[1] These devices include computer displays, infrared sights, global positioning systems (GPS), night vision and a variety of other sensor technologies. More than 80% of the energy needed to power these devices comes from primary (disposable) batteries. It is estimated that a brigade will consume as much as seven tons of batteries in a 72-hour mission at a cost of $700,000.[2]

A recent comprehensive study on the energy needs of the future warrior published by the National Academy of Sciences in 2004 made a variety of recommendations for average power systems from 20 to 1,000 watts.[3] For lower power systems recommendations included pursuing science and technology initiatives focused on 1) secondary (rechargeable) battery technologies with an energy density of 300 watt-hour per kilogram (Wh/kg),* 2) hybrid power sources, and 3) fuel cells (with greater than 6 wt% hydrogen storage).

Improved secondary batteries may be the ideal solution for military power systems due to their ease of use and public acceptance. However, 300 Wh/kg represents a two-fold improvement in specific energy density and that is not likely anytime soon. Current lithium-ion (Li-ion) batteries, at about 150 Wh/kg, fall well short of the energy density that is required. Future battery technology may not be a viable solution since many experts do not predict more than a two-fold improvement in Li-ion battery systems over the next 10 years.[4] Thus, most auto companies have abandoned all electric vehicles in favor of fuel cells and hybrid vehicles.

Hybrid systems typically combine low energy and high power components with high energy and low power components. Typical configurations include capacitors and fuel cells or batteries and fuel cells. A hybrid system can have both high energy and high power density; if combined effectively, these components can work synergistically to provide greater amounts of energy and power than the individual components.

Fuel cells have very high specific energy densities but achieving high energy values will depend on the energy density and the storage method of its fuel. Improved methods of safely and efficiently storing larger amounts of hydrogen will be a key development area for portable fuel cell power systems.

For fuel cells and hybrid systems to become more practical for common applications, the storage of hydrogen must first be addressed. This paper describes advanced hydrogen storage materials being developed by Savannah River National Laboratory (SRNL) and other related Department of Energy (DOE) programs. The article also identifies leading candidates and systems that can be applied to DoD portable power applications. The plans and initial activities of a new DoD Warfighter Portable Power Center located at the Center for Hydrogen Research are also described.

HYDROGEN

Hydrogen at 33,000 Wh/kg has one of the highest specific energy densities of any other fuel; it is almost three times greater than the specific energy density of gasoline. For many applications the specific energy density or the amount of energy per unit weight of the fuel is often critical. This is especially true in warfighter and other man-portable power applications where weight of the entire system needs to minimized. Table 1 compares the specific energy density of various fuels.

Hydrogen is a high energy fuel, and it is often used as NASA's fuel of choice for rockets and space exploration platforms. Another advantage of hydrogen is its higher energy conversion efficiency (i.e., the ratio between the useful output and the input) when used in a fuel cell (50-60%) compared to the efficiency of an internal combustion engine (15-25%). This would allow a soldier in the field to obtain two to four times more energy from hydrogen than can be obtained by converting the same amount of energy from another fuel to useful work. With 6 wt%† storage and a 50% energy conversion efficiency, a hydrogen fuel cell system could generate an energy density of 1000

Table 1. Specific energy density of various fuels.

Fuel	Specific Energy Density, Wh/kg
JP-8 and Gasoline	12,000
Methanol	5,600
Ethanol	7,500
Hydrogen	33,000
Hydrogen (6%)	2,000

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14. ABSTRACT
From Person Digital Assistants (PDAs) to cell phones our high-tech world is demanding smaller, lighter weight and higher capacity portable power devices. Nowhere has this personal power demand been more evident than in today's US warfighter. The modern warfighter is estimated to carry from 65 to 95 pounds of supplies in the field with more than 30 pounds of this dedicated to portable power devices. These devices include computer displays, infrared sights, global positioning systems (GPS), night vision and a variety of other sensor technologies. More than 90% of the energy needed to power these devices comes from primary (disposable) batteries. It is estimated that a brigade will consume as much as seven tons of batteries in a 72-hour mission at a cost of $700,000.

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Table 2. Comparison of various soldier power systems.

Technology	Specific Energy Density, Wh/kg	Average Power, W
Fuel Cell/H_2 (5000 psi)	1,033	20
Fuel Cell/$NaBH_4$	556	20
Direct Methanol Fuel Cell	478	20
Li-ion battery*	170	20
Fuel Cell/H_2, 6%	659	100
Direct Methanol Fuel Cell	581	100
Li-ion battery*	170	100

*State-of-the-Art

Wh/kg or almost seven times that of current Li-ion batteries. For example, a recent DoD challenge sought the development of a 20 watt warfighter system that lasts through a 96-hour mission and weighs less than 4 kg (see article titled "Lightweight Wearable Power Energized by Pentagon's Prize Program" on page 11.) This requirement can be restated as a power system with a specific energy density of 500 Wh/kg. Table 2 compares several soldier energy sources for 20 W and 100 W average power for 72-hour missions.[3]

From Table 2, it can be seen that several fuel cell systems using either direct hydrogen, metal hydride or direct methanol all have the ability to achieve system energy densities in excess of 500 Wh/kg. Also all of the fuel cell systems have specific energy densities three to five times that of the latest Li-ion secondary battery technology. By further increasing the hydrogen storage density in these fuel cell systems to 10 wt% or higher, it could easily lead to systems with energy densities in excess of 1000 Wh/kg.

While hydrogen has a very high specific or gravimetric energy density, the opposite is true with respect to its volumetric energy density or the amount of energy per a given volume of fuel in watt-hour per liter (Wh/l). As a gas, hydrogen must be compressed to pressures of 5000 pounds per square inch (psig) or higher to obtain a reasonable volumetric energy density. Even liquefied hydrogen only has a volumetric energy density about a fourth of that of gasoline. Hydrogen storage technologies thus become key to the successful application of hydrogen technology. Research on more efficient ways of storing hydrogen, at even higher volumetric densities than liquid hydrogen, is actively being pursued all over the world for a variety of power applications ranging from automobiles to laptops.

HYDROGEN STORAGE

The Savannah River National Laboratory has been working with the DOE, other national laboratories, universities and industry to develop high capacity, low weight hydrogen storage materials for automotive applications. This has often been referred to as the hydrogen "Grand Challenge". The goal of the DOE Hydrogen Program is to develop onboard hydrogen storage for passenger vehicles that achieves greater than a 300-mile driving range without compromising passenger/cargo space, performance or cost. This requires meeting targets which include: hydrogen capacity, operating temperature range (-40 to +85°C), hydrogen supply rate/refueling rate (0.2 grams of hydrogen per second per kilowatt of power and refueling time less than three minutes for five kg of hydrogen), system cost, fuel cost, safety, reliability, cycle life, efficiency, etc.[5]

Over the past several years, while many new materials have been developed under the DOE program, most have fallen short of the challenging automotive-based targets. Figure 1 shows the current status of the DOE program with respect to the gravimetric and volumetric targets. Because hydrogen exists as such a lightweight gas, storing it at a high gravimetric and volumetric density has been one of the greater hydrogen storage challenges. From Figure 1, the DOE system targets of 45 grams per liter (g/l) and 6 wt% hydrogen and 80 g/l and 10 wt% hydrogen for 2010 and 2015, respectively, are represented by the box in the top right hand corner of the graph. Also in Figure 1 some preliminary system results for various hydrogen storage materials are plotted and compared to compressed and liquid hydrogen systems. It is obvious from Figure 1 that none of the materials developed to date, including compressed gas and liquid hydrogen, meet the current DOE capacity targets when compared on an overall system basis.

To help attain their hydrogen storage goals, DOE has funded three multi-disciplinary Centers of Excellence in hydrogen storage materials development and a new Center of Excellence in hydrogen storage engineering and systems development. The three materials centers in Metal Hydrides, Chemical Hydrides and Adsorbents are all led by various DOE National Laboratories with participation by various university, industrial and other federal laboratory partners. SRNL has recently been selected by

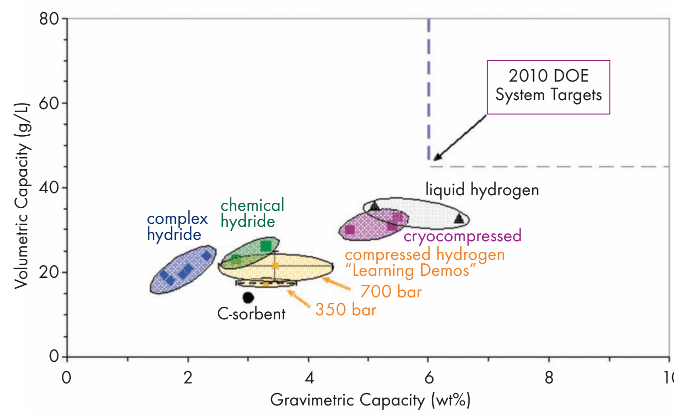

Figure 1. Current status of DOE hydrogen storage targets.[5]

> Hydrogen Storage Engineering Center
> http://www1.eere.energy.gov/hydrogenandfuelcells/storage/index.html

the DOE to lead the new Hydrogen Storage Engineering Center, which is tasked to work with the other three centers to develop and test subscale engineered systems of the most promising candidate hydrogen storage materials.

While the DOE hydrogen storage challenge is still moving forward, based on automotive requirements SRNL believes that many of the new materials that have been developed may already have potential for portable power applications. For example, many portable power applications do not require the same cost targets that are required by the transportation marketplace. Also options like fuel cartridge swapping and replacement are much more suitable and economical for smaller portable power systems than for onboard vehicle systems.

Table 3 shows some of the high capacity hydrogen storage

Table 3. **High capacity hydrogen storage materials.**

Formula	Weight % Hydrogen
NH_3BH_3	19.6 (12% practical)
$LiBH_4$	18.3 (requires high temperatures)
$Al(BH_4)_3$	16.8
$Mg(BH_4)_2$	14.8
$LiAlH_4$	10.6
$NaBH_4$	10.6 (7.6% with 50% H_2O)
AlH_3	10.0
$NaAlH_4$	7.4 (5.6% practical)

materials that are being investigated by SRNL and the other centers for the DOE hydrogen storage program. While many of these appear to have the potential to meet the DOE 2010 system target of 6 wt% hydrogen, most cannot meet many of the other DOE targets because of their high operating conditions (e.g., temperature and pressure) or associated costs, which make them unsuitable for onboard passenger vehicle systems. Many of these candidate materials with hydrogen capacities from 10 to almost 20 wt% may be ideal candidates for military portable power applications, leading to system specific energy densities of 1500 to 3000 Wh/kg.

Many of the materials in Table 3 have a high volumetric hydrogen capacity. For example Alane (AlH_3) has twice the hydrogen capacity of liquid hydrogen, making it a good potential candidate for portable power systems. Some of the systems in Table 3 can simply be heated to release some or all of their hydrogen, while others can be slowly reacted with water or other liquids to release their contained hydrogen as well as some of the hydrogen from the water reagent. Sodium borohydride ($NaBH_4$) is an example of this type of material; when combined with a catalyst, it can react with water to provide hydrogen. $NaBH_4$ has already found some uses in military and other portable power applications.

Many of the hydrogen storage materials being developed in the US are being carried out under the DOE's National Hydrogen Storage Project, which includes independent projects and Centers of Excellence (CoEs) in applied hydrogen storage R&D as well as DOE Office of Science basic research in hydrogen storage.[5] Two of the materials centers that are actively involved in exploring materials, such as those described in Table 3, are the Metal Hydride Center of Excellence (MHCoE) and the Chemical Hydrogen Storage Center of Excellence (CHSCoE). Both centers are tasked to develop hydrogen storage materials that meet system targets for automotive hydrogen storage applications.

The MHCoE is primarily focused on metal and chemical hydride materials that can be recharged with hydrogen under conditions that are compatible with onboard vehicle operations. These materials are typically referred to as reversible hydrides. Some of the materials being investigated by the MHCoE include several boron (B) and aluminum (Al) based materials that have theoretical hydrogen capacities ranging from 7 to 18 wt% hydrogen (see Table 3). Despite their high hydrogen capacity many of these materials have not yet been shown to be fully reversible under conditions that are compatible with onboard vehicle storage. Some of these materials like $NaAlH_4$ have been found to be only partially reversible and some like $LiBH_4$ require over 500°C to release its hydrogen, which is too high a temperature for practical automotive applications. Another material being examined by SRNL and others in the MHCoE is AlH_3. This material is able to readily release 10 wt% hydrogen at practical conditions but it requires more than 100,000 atmospheres of pressure to recharge it with hydrogen. SRNL and Brookhaven National Laboratory have both been working on different ways to recharge and reform this material and so far have shown some success using both electrochemical and chemical synthesis methods, respectively.[6]

While the materials being developed by the CHSCoE are similar to those being examined by the MHCoE, the focus of the CHSCoE is to develop non-reversible chemical hydride materials. These are materials that would give up their hydrogen on board an automobile but then the material itself would have to be removed from the vehicle to be recharged by a chemical process. One of the early materials developed by the CHSCoE was sodium borohydride ($NaBH_4$). This material has found its way into several military portable power applications but was found not to be practical for vehicle applications. Today the CHSCoE is primarily focused on Ammonia Borane (NH_3BH_3), a material with a high 20 wt% theoretical hydrogen capacity. Work at the CHSCoE is mainly aimed at improving the quantity and rate of hydrogen released at the lowest temperatures possible and developing more energy and chemically efficient methods to regenerate the spent fuel.[7]

In addition to the efforts of the two Centers of Excellence described here briefly, there are many other US and international efforts underway to develop new efficient and high capacity hydrogen storage materials for automotive and other applications. The US DOE program has focused mainly on automotive applications and as a result many promising materials that may be appropriate for applications other than automobiles have not been pursued. SRNL has proposed the development of a new center that can leverage much of the work that has already been performed by DOE to provide the DoD, and eventually commercial market, with a reliable and lightweight portable power alternative.

DOD WARFIGHTER PORTABLE POWER CENTER

SRNL has proposed and is seeking FY10 funding for a unique Warfighter Portable Power Development Center focusing on 20-200 W soldier power systems. SRNL plans to team with

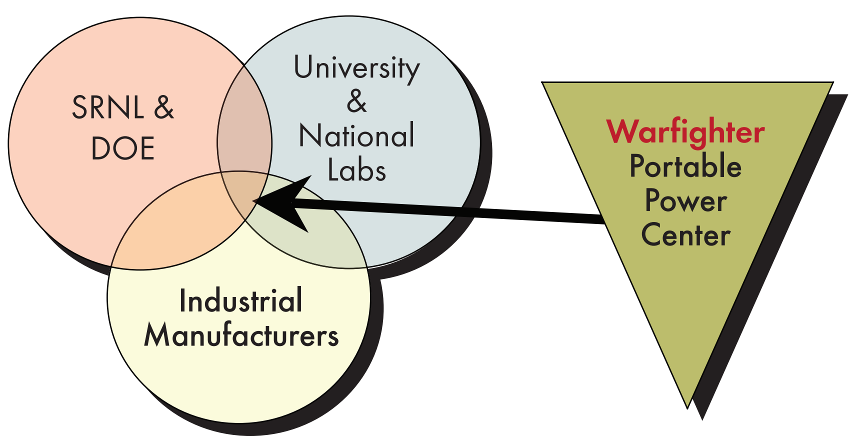

Figure 2. **Warfighter Portable Power Center schematic.**

universities, national laboratories and industrial partners to further enhance its already strong capabilities and talents. The unique feature of the proposed center is its focus on inviting manufacturers and developers of fuel cells, batteries, capacitors and other electrochemical components and devices to join in integrating their components and devices into a final product, which functions as a complete military power pack – a system solution. Figure 2 shows a schematic of the proposed center's organization and its inter-relationships.

The driver for this type of center is twofold. First is the need to substantially increase the operational life and reduce the weight of battery packs often used by the military. The second driver is to leverage off of the many novel hydrogen storage materials and systems that are coming out of the DOE and other federal hydrogen programs. The goal of the center is to develop complete power source systems for a variety of portable warfighter applications. The primary approach of the center will be to identify several >10 wt% hydrogen storage systems and to combine them with fuel cells and other energy storage devices to arrive at an optimal power source solution. As described earlier, a fuel cell or a fuel cell hybrid portable power system with over 1000 Wh/kg is possible if a 10 wt% or higher hydrogen storage density material is available. During the first year of the center's operation a proof-of-concept system coupled with an existing military capable fuel cell will be demonstrated. Following a successful proof-of-concept, a field-ready prototype system could be developed with commercial partners during the next 12 to 18 months.

While increasing the specific energy density of warfighter

PARTNERSHIPS

The objective of the DOD Warfighter Portable Power Center is to partner with commercial fuel cell, battery, vessel and other component manufacturers as well as university and other national laboratory experts to develop and test complete power systems for military applications. To expedite this effort SRNL will partner with the Center for Hydrogen Research (CHR), a unique non-profit organization and facility located adjacent to SRNL facilities near Aiken, South Carolina. The role of the CHR is both to provide the creative environment and to serve as a catalyst to bring scientists and technologists from various organizations and disciplines together to help solve problems and develop unique solutions. The needs of the warfighter for high capacity and reliable power are an excellent example of the type of problems the CHR can address. The unique feature of the proposed center is its focus on inviting manufacturers and developers of fuel cells, batteries, capacitors and other electrochemical components and devices to partner in integrating their component parts and devices into a final product, which functions as a complete military solution.

The Center is aimed at providing the military with a complete solution to the future warfighter power needs.

The Center for Hydrogen Research

The CHR is a 60,000 square foot, $10 million facility designed for hydrogen research, development, and commercialization. CHR tenants include the Savannah River National Laboratory, Toyota Technical Center R&D lab, offices for the International Fusion Experiment project, and University of South Carolina - Aiken research on biohydrogen. The CHR and SRNL have under development a $1.0 million DOE-sponsored project to evaluate backup fuel cell power using metal hydride storage and electrolysis technologies. The CHR also operates a hydrogen refueling station and a hydrogen fueled internal combustion vehicle.

Savannah River National Laboratory

SRNL has more than 50 years of experience in developing and applying hydrogen technology, both through its national defense activities and its hydrogen energy activities with the DOE and industry. The hydrogen technical staff at SRNL comprises more than 90 scientists, engineers and technologists, and it is believed to be the largest such staff in the US. Forty of the SRNL hydrogen professionals have research facilities in the CHR. SRNL has ongoing R&D initiatives in a variety of hydrogen storage areas, including metal hydrides, complex hydrides, chemical hydrides and carbon nanotubes. SRNL has more than 25 years of experience in metal hydrides and solid-state hydrogen storage research, development and demonstration.

SRNL has been active in teaming with academic and industrial partners to advance hydrogen technology and has participated in projects to convert public transit and utility vehicles for operation on hydrogen fuel. Some major projects include the H2Fuel Bus and an Industrial Fuel Cell Vehicle (IFCV) also known as the GATOR™. Both of these projects were funded by DOE and cost shared by industry.

SRNL is a recognized international leader in hydrogen storage with added expertise in hydrogen production, fuel cells and battery technology. SRNL has excellent access to worldwide hydrogen technology information and is the DOE lead for the Hydrogen Storage Engineering Center of Excellence.

power systems is one of the main objectives of this program, another goal of the center is to optimize the power systems to military conditions and operations. These include improving their ease of use and reliability in the field and harsh environments, employing hybrid technologies to minimize the impact of using air breathing devices, minimizing heat and noise signals, and lowering overall system and deployment costs. The Warfighter Portable Power Center at the Center for Hydrogen Research would serve as catalyst and an incubator for the development, assembly and evaluation of future high energy military and eventually commercial portable power systems.

SUMMARY

The Savannah River National Laboratory with its primary partner the Center for Hydrogen Research has proposed a novel Portable Power Center aimed at supporting the DoD warfighter. The Center's objective is to leverage the current and past research on high capacity, hydrogen storage materials performed by SRNL and the other DOE National Laboratories for automotive applications. Some of these high capacity materials contain 10 to 20 wt% hydrogen but for one reason or another are not suitable for automobiles systems. However, many of these materials can still be viable for portable power systems. Combined with a small fuel cell these materials can lead to power packs that achieve specific energy densities of 1000 Wh/kg, more than 2 to 3 times that of today's best battery systems. The role of the new center will be to partner with industrial fuel cell, battery, other component manufacturers and system integrators to arrive at complete power solutions for the future warfighter.

NOTES & REFERENCES

* *Energy density* is the amount of energy stored per unit mass.

† Weight percentage (wt%) hydrogen is the percentage of hydrogen by weight in the storage material compared to the weight of the overall storage material.

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[7] 2008 Overview – DOE Chemical Hydrogen Storage Center of Excellence FY2008 Annual Progress Report, http://www.hydrogen.energy.gov/annual_progress08.html

Dr. Theodore (Ted) Motyka has a BS, an MS and a PhD all in Chemical Engineering. Dr. Motyka received his PhD degree from the University of Colorado in 1979 and then joined the Savannah River Site in 1980. Dr. Motyka is currently serving as the Hydrogen Program Manager for the Savannah River National Laboratory. During the past 15 years, Dr. Motyka and his team have been actively involved in the development and demonstration of hydrogen as an alternative energy carrier. Dr. Motyka has led several state initiatives for hydrogen energy, including an organization that produced the South Carolina Hydrogen and Fuel Cell Alliance. He is also responsible for initiating the new Center for Hydrogen Research in Aiken County. Recently, Dr. Motyka and his colleague Dr. Donald Anton were named as the Assistant Director and Director, respectively, of the new DOE Hydrogen Storage Engineering Center of Excellence for Hydrogen Storage.

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